MEDICAL IMAGING CENTERS IN CENTRAL INDIANA:

OPTIMAL LOCATION ALLOCATION ANALYSES

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MEDICAL IMAGING CENTERS IN CENTRAL INDIANA:

OPTIMAL LOCATION ALLOCATION ANALYSES

While optimization techniques have been studied since 300 B.C. when Euclid first considered the minimal distance between a point and a line, it wasn't until 1966 that location optimization was first applied to a problem in healthcare. Location optimization techniques are capable of increasing efficiency and equity in the placement of many types of services, including those within the healthcare industry, thus enhancing quality of life. Medical imaging is a healthcare service which helps to determine medical diagnoses in acute and preventive care settings. It provides physicians with information guiding treatment and returning a patient back to optimal health. In this study, a retrospective analysis of the locations of current medical imaging centers in central Indiana is performed, and alternate placement as determined using optimization techniques is considered and compared. This study focuses on reducing the drive time experienced by the population within the study area to their nearest imaging facility. Location optimization models such as the *P*-Median model, the Maximum Covering model, and Clustering and Partitioning are often used in the field of operations research to solve location problems, but are lesser known within the discipline of Geographic Information Science. This study was intended to demonstrate the capabilities of these

powerful algorithms and to increase understanding of how they may be applied to problems within healthcare. While the *P*-Median model is effective at reducing the overall drive time for a given network set, individuals within the network may experience lengthy drive times. The results further indicate that while the Maximum Covering model is more equitable than the *P*-Median model, it produces large sets of assigned individuals overwhelming the capacity of one imaging center. Finally, the Clustering and Partitioning method is effective at limiting the number of individuals assigned to a given imaging center, but it does not provide information regarding average drive time for those individuals. In the end, it is determined that a capacitated Maximal Covering model would be the preferred method for solving this particular location problem.

Aniruddha Banerjee, Ph.D., Chair

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Introduction

During the first decade of this century, the quantity of medical imaging performed in the United States increased significantly. In 1995, 79 Computed Tomography (CT) exams were performed for each 1,000 people in the United States. By 2011, this number had increased to 274 (Organisation for Economic Cooperation and Development (OECD), 2015). The number of medical imaging centers increased during this same period. In 2003, there were 5,163 imaging centers in the U.S. By 2012, this number had swelled to 7,074 (Proval, 2013). More recently, these numbers have been in decline. A report published by the Harvey L. Neiman Health Policy Institute observed that in 2010, Medicare spending on medical imaging had dropped by 21% since its peak in 2006. Americans with private insurance similarly saw a reduction of 5.4 percent in medical imaging spending from 2009 to 2010 (Duszak, 2012). Medical imaging centers are now slowly consolidating. Several possible reasons for this change include technological maturation, the development of best practice guidelines, increased radiation awareness, clinical information availability and integration, cost effectiveness awareness and initiatives, market saturation, and utilization management tools (Duszak, 2012). The Affordable Care Act (ACA), which began implementation in 2010, has affected the medical imaging industry. The ACA mandated the creation of accountable care organizations (ACOs). The purpose of an ACO is to tie provider reimbursements to quality metrics and to reduce the total cost of care for an assigned population of patients. The ACA also moves away from the fee-for-service payment model toward a bundled payment model in which a single payment is made to providers or health care facilities for all services to treat a given condition (Centers for Medicare and Medicaid Services, 2015). A 2013 survey of *Diagnostic Imaging* readers found that 66% of the polled readers (61.2% of which were radiologists) reported a hiring freeze within their radiology group due to the impact of the Affordable Care Act, reimbursement cuts, and future payment models ("Survey," 2013). 32.5% reported a freeze on all new purchases of equipment while 50% reported that they would only purchase new equipment if there was a demonstrable return on investment. 39.9% of those surveyed advised that they were seeing slight effects of reimbursement cuts due to the Affordable Care Act while 37.4% reported major impacts of reimbursement cuts. There is some concern in the radiological medical community regarding the long term effects of synergistic efforts intended to reduce the use of medical imaging. The author of the Neiman Report specifically cites the potential change in clinical outcomes from positive to negative if attempts to suppress the growth of medical imaging continue (Duszak, 2012). A counter argument to this concern is that incidental findings would likewise be reduced further shrinking medical costs (Lumbreras, Donat, & Hernández-Aguado, 2010).

While many organizations have observed national trends in the use of medical imaging, little information is readily available regarding the state of medical imaging utilization in Indiana. *Radiology Business* observed that there were 131 imaging centers in the state in 2013 (Proval, 2013), but more in-depth information regarding this industry within the state is difficult to find.

Medical imaging centers form an important part of our preventive health care system. Some illnesses, such as breast cancer and lung cancer, are treated more successfully if they are caught early (The National Cancer Registration Service, Eastern Office, 2015) , and reducing structural barriers (including time and distance required to travel) can increase community access to preventive services such as breast cancer screening (Baron et al., 2008). Regarding breast cancer screening in particular, it is important to note that the U.S. Preventive Services Task Force (USPSTF) has recently found that mammography is most beneficial for women ages 50 to 74. While screening for women between the ages of 40 and 49 years is beneficial, the benefit is small, and the number of false-positives and unnecessary biopsies were significant (Siu, Bibbins-Domingo, & Grossman, 2015). The USPSTF has further recommended that routine screening should end at age 74, and that screening mammograms should be performed every two years instead of every year. It remains to be seen if these new recommendations will affect insurance reimbursements, but American Cancer Society national volunteer president Elizabeth T.H. Fontham, MD, believes it is likely that private insurance and Medicare will stop paying for annual mammogram screening for women in their 40s and over 74 (“New Mammogram Screening Guidelines FAQ,” n.d.). If these new recommendations are reinforced by limited insurance reimbursements for screening performed outside of the guidelines, medical imaging centers can expect to a reduction in the use of mammography services. Many other studies have demonstrated the effect of physical access on health care utilization and health outcomes (Baume, Helitzer, & Kachur, 2000; Buor, 2003; Stock, 1983; Tanser, Hosegood, Benzler, & Solarsh, 2001). Facility location decisions which utilize optimization methods may increase ease of access and thus contribute to a healthier community.

Historically, healthcare facility locations have been influenced by the presence of population centers, the position of donated land, and the preferences of financial donors and supporting institutions. During World War II, the formal discipline of operational research (OR) developed to solve the problems of military planners. OR employs advanced analytical methods including mathematical modeling, statistical analysis, and mathematical optimization to help make better decisions ("Operations research," 2015). Facility location is a sub-discipline of OR "concerned with the optimal placement of facilities to minimize transportation costs while considering factors like avoiding placing hazardous materials near housing, and competitors' facilities" ("Facility location problem," 2015).

Location allocation modelling was first used in a health study by Gould and Leinbach in 1966. In their study, an algorithm was implemented "to locate a series of hospitals in Guatemala and determine their optimal capacity in order to best serve the local population given the existing road networks" (Gould & Leinbach, 1966, p. 542). Additional facility location studies related to the provision of healthcare have included the use of the *P*-Median model to locate five new primary group practices in the service area surrounding Lansing, Michigan (Bennett, 1981); a comparison of four location allocation models to locate optimal sites for physicians' surgeries in two East Kent towns (Curtis, 1982); a hierarchical *P*-Median model used to optimize the number and locations of hospitals in the state of Indiana (Momani, 1988); a location allocation model used to maximize the survival of acute coronary disease patients in rural upstate New York (McLafferty & Broe, 1990); an expanded Maximal Covering model used to maximize participation in preventive healthcare programs in Fulton County, Georgia and Montreal, Canada (Verter & Lapierre, 2002); the use of location allocation models to determine medical service locations for large-scale emergencies in Los Angeles, California (Jia, Ordóñez, & Dessouky, 2007); a Maximal Covering model used to identify the optimal locations for the 129 hospitals in the state of Michigan (Messina, Shortridge, Groop, Varnakovida, & Finn, 2006); and finally, a Capacitated Maximal Covering model used to find the best locations for community health centers in the state of Georgia (Griffin, Scherrer, & Swann, 2008).

Definitions

P-Median Problem: a location allocation model designed to "to minimize the total demand-weighted travel distance between demands and facilities" (Owen & Daskin, 1998).

Maximal Covering Problem: a location allocation model designed to minimize the maximum distance between any demand node and its nearest facility (Owen & Daskin, 1998).

Clustering: a procedure which allows an analyst to "create groupings of features in a point or area layer based on the distance or travel cost between them, with or without capacity restriction" (*TransCAD*, 2015, p.64).

Regional partitioning: an algorithm used when there is a need "to create compact and balanced areas that are composed of smaller geographic areas" (*TransCAD*, 2015, p. 64).

Design

This study was designed to evaluate the ability of different location allocation models to optimize the location and distribution of medical imaging centers within central Indiana. Using the *P*-Median model and the Maximal Covering model algorithms available within the TransCAD 6.0 routing and logistics software, optimum sites for medical imaging centers were identified based on additional parameters described by the author. A network partition model also available within TransCAD 6.0 was used to evaluate the efficiency of the current imaging center locations. While TransCAD 6.0 was used for this particular study, most GIS software packages are capable of solving location allocation problems. The hardware utilized for this study was a PC with the following specifications: 3.10 GHz Intel Core i5-2400 Quad Core Processor and 8.00 GB of System Memory.

The following five hypotheses were developed to guide the analysis of the results of this study:

1. Geographical areas will be identified which currently require driving more than 30 minutes to reach a medical imaging center. The 30-minute drive time cut off has been used in a number of studies assessing spatial access to health care services (Lian, Struthers, & Schootman, 2012; Mao & Nekorchuk, 2013; Wang & Luo, 2005).
2. The *P*-Median model solution will be more efficient in terms of overall travel time than the current placement of medical imaging centers in central Indiana.

3. The *P*-Median model solution will require fewer medical imaging centers to efficiently service central Indiana.
4. The Maximal Covering model solution will be more efficient in terms of maximum travel time than the current placement of medical imaging centers in central Indiana.
5. The Maximal Covering model solution will require fewer medical imaging centers to equitably service central Indiana. In this case, service was deemed to be equitable if no population group was required to drive more than 30 minutes for medical imaging.

Data

Imaging Center Locations

There are many types of medical imaging including computed tomography (CT), magnetic resonance imaging (MRI), x-ray, molecular imaging, and ultrasound imaging. For the purposes of this study, imaging centers which provide either CT, MRI, or x-ray services were considered as these types of medical imaging are commonly ordered across many physician specialties. It was also assumed that each imaging center had only one machine capable of providing each type of service. For example, if a center was identified as providing only X-Ray services, it was assumed that the center had only one X-Ray machine.

Table 1 displays the number of imaging centers providing each type of imaging service:

Table 1
Imaging Centers Identified by Type of Imaging Services Available

Type of Services Provided	Number of Imaging Centers
X-Ray Only	8
CT Only	2
MRI Only	1
X-Ray and CT	4
X-Ray and MRI	5
CT and MRI	0
X-Ray, CT, and MRI	63

The locations of medical imaging centers equipped to perform at least one of these three types of services were obtained from four Medicare approved accreditation organizations: 1) The Intersocietal Accreditation Commission, 2) The American College of Radiology, 3) RadSite, and 4) The Joint Commission on the Accreditation of Healthcare Organizations (JCAHO) (Medicare, Baltimore, & Usa, 2015). Many of the imaging facilities holding accreditation from the Intersocietal Accreditation Commission were accredited in myocardial perfusion imaging, adult thoracic imaging, intracranial cerebrovascular testing, peripheral venous testing, extracranial cerebrovascular testing, or adult stress testing rather than CT, MRI, or x-ray. As a result, only one of the facilities used for the analysis had this particular accreditation. The RadSite certification and accreditation site contained information about individual physician practices and groups which have their own radiology equipment. Primary care providers with accredited radiology facilities in their offices were not excluded from this analysis although a patient would likely need to be established with one of the practice physicians prior to having imaging performed there. Likewise, hospital emergency rooms with radiology equipment were not excluded, but the same caveat applies.

Table 2 displays the number of imaging centers accredited by each entity:

Table 2
Imaging Centers Identified by Type of Accreditation

Accrediting Entity	**Number of Imaging Centers**
JCAHO	6
RadSite	18
The American College of Radiology	38
The American College of Radiology, JCAHO	14
The American College of Radiology, RadSite	6
The Intersocietal Accreditation Commission	1
Total:	83

A total of 83 accredited imaging centers were identified in the eleven central Indiana counties (Boone, Brown, Hamilton, Hancock, Hendricks, Johnson, Madison, Marion, Morgan, Putnam, and Shelby).

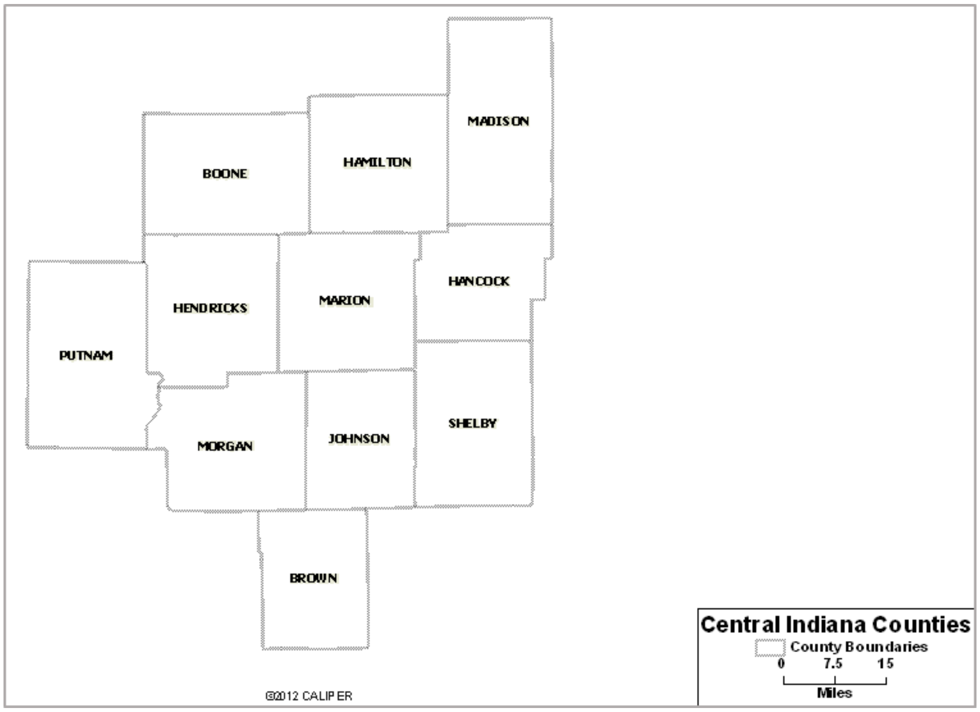

Figure 1. Central Indiana Counties.

Imaging centers were identified as either free-standing ambulatory imaging centers or hospital-based imaging centers. Free-standing ambulatory imaging centers are not located within a hospital and do not require use of emergency room services or hospital admission. Hospital-based imaging centers may require hospital admission or use of the emergency room before imaging services can be rendered. Thirty-four imaging centers were classified as hospital-based while forty-nine were classified as free-standing.

For this particular study, it was assumed that each imaging center had only one piece of equipment for each type of service provided. For example, if an imaging center was identified as providing CT imaging and MRI imaging, it was assumed that the imaging center had one CT scanner and one MRI machine. A random survey of a small number of the centers revealed that this was not always the case. Table 3 provides the details of the survey.

Table 3
Imaging Equipment Survey

Imaging Center	CT	MRI	X-Ray
American Health Network Westfield	0	0	1
Center for Diagnostic Imaging – Carmel Location	1	2	1
Community Hospital Anderson	2	1	4
Community Imaging Center North	1	1	2
Eskenazi Health	3	2	6
Indiana Orthopaedic Hospital – Brownsburg	1	1	4
Indiana University Health – University Hospital	4	3	6
Methodist Sports Medicine Center North	0	1	3
Northwest Radiology Network, P.C.	1	2	1
St. Francis Imaging Center – Smith Valley Road	1	1	1

Shapefiles of U.S. Census Block Groups: Central Indiana (2013)

Block group shape files for the year 2013 for each of the eleven central Indiana counties were downloaded from the U.S. Census website (U. S. Census Bureau, 2014). 1,197 block groups were identified in the study area.

U.S. Census Block Group Total Population: Central Indiana (2013)

The 2013 total population for each block group was downloaded from the American FactFinder website, another service of the U.S. Census. The selected table, B01003, contains the total population for each block group as calculated in the 2009-2013 American Community Survey 5-Year Estimates (U.S. Census Bureau, 2014). A total population of 1,912,155 was identified for the study area.

Standard Geographical File of Street Intersections and Nodes: Central Indiana

Street segments and intersection nodes within the eleven central Indiana counties were already available within the TransCAD 6.0 software program. These are based on U.S. Census files with additional enhancements made by the Caliper Corporation (*TransCAD*, 2015). Stated speed limits for each street segment were not included with these layers and were added later as will be discussed in the methods section. In the eleven central Indiana counties used for this analysis, there were 194,514 street segments and 158,006 street intersections. This layer is topologically integrated allowing for the creation of a street network and for solving facility location problems.

Methods

Pre-Analysis Data Preparation

A number of preliminary steps were required to prepare the data for analysis. The first step involved joining the population data to the block group shapefiles based on the block group identification number attribute in each file. Once joined with the population data, the block group polygon file was converted to a centroid point file. A polygon shape file displays the shape of the block group area while a point file simply displays the location of each block group in the form of a point placed at the center of the block group polygon. For the purposes of this study, only a point file was needed.

Next, a Microsoft Excel file containing the names and addresses of the identified medical imaging centers was imported into TransCAD 6.0 and geocoded. The result was a point file with the following attributes: imaging center name, imaging center address, latitude, and longitude. One imaging center, Select Specialty Hospital of Beech Grove, Indiana, had an address which was unable to be confirmed by the JCAHO accreditation site, so it was left out of the analysis. The remaining 82 imaging centers were geocoded successfully.

The location allocation algorithms in TransCAD 6.0 require the creation of a street network and a cost matrix in order to arrive at a solution. The ultimate goal of this analysis was to reduce the amount of travel time required to drive to an imaging center. A street network based on travel time was necessary to reach this goal. While the street segments in TransCAD 6.0 did have an attribute indicating the length of the street segment, they lacked both speed and travel time attributes.

Street segments in TransCAD 6.0 have a Tiger/Line File Census Feature Class Code (CFCC) attribute which tells what type of road each segment is. For example, class A41 indicates a “local, neighborhood, and rural road, city street, unseparated.” Speed limits in the United States are set by each state or territory and are often unpublished. An attempt was made to collect accurate posted speed limits for each street segment in the study area. Email communication with three different individuals in three different metropolitan planning or department of transportation offices was recommended and initiated, but, unfortunately, no return emails were received. As a result, the speeds selected for each street segment were based on advice provided by Dr. Rudy Banerjee during the initial development of this analysis. Table 3 displays the CFCC classifications which were identified within the selected street segments, and the speed limits which were assigned to each type of road:

Table 4
TIGER/Line File Feature Class Code

CFCC	**Type**	**Speed (mph)**
A11	Primary Road	55
A15	Primary Road	55
A20	Secondary Road	55
A25	Secondary Road	55
A40	Local Road	35
A45	Local Road	35
A50	Vehicular Trail (4WD)	25
A51	Parking Lot Road	25
A51	Bike Path	25
A54	Service Drive	25
A56	Alley	20
A56	Internal Census Use	20
A57	Walkway	20
A63	Ramp	25

It is important to note that certain types of street segments were assigned speed limits which may or may not be acceptable. For example, bike paths were assigned a speed of 25 miles per hour and walkways were assigned a speed of 5 miles per hour. These speed assignments were made before the type definitions of the Census Feature Class Codes were known to the author.

The street segment data was exported to an Excel spreadsheet which allows for greater flexibility in filtering data than does TransCAD 6.0. Speed limits were entered based on TIGER/Line File CFCC classification. The speed limit data was then transferred from the Excel document into the attribute table for the street segments in TransCAD 6.0. In order to calculate the travel time in minutes for each street segment, a second new column was created in the attribute table and the formula (length/speed) *60 was used to fill the column.

The last step to complete before building the street network was to locate both the imaging centers and the block group population points within the street intersection node layer. This step was necessary in order to allow the network to successfully locate both point layers on the network when running location allocation algorithms. Locating was accomplished by selecting the closest street intersection node to each imaging center and block group population point. During this process, a number of imaging centers were found to be closest to the same street intersection node. As a result, a total of 74 street intersection nodes were associated with the 82 imaging centers. All 1,197 block group nodes were successfully located within the street intersection node layer.

Finally, a street network based on travel time in minutes was created. While turn penalties modelling the cost or delays associated with making turns were incorporated into the network, a time of day analysis was not performed. Thus, the additional delays which drivers experience during high traffic times (e.g., between 8 a.m. and 9 a.m.) were not taken into account in this study. With the street network layer active in TransCAD 6.0, a cost matrix was developed. The cost matrix calculates the travel time from each origin point (the imaging centers) to each destination point (the population nodes) and presents the results in the form of a table. The cost matrix table is then used by the location allocation algorithm to determine the least "expensive" street segments to use when solving the allocation problem.

Network Partitioning Using the Shortest Path Procedure

In order to evaluate the efficiency of the current medical imaging center network in central Indiana, it was necessary to use a shortest path procedure to partition the street network around the current imaging centers. The partitions were created based on travel time, and each street segment was assigned to its nearest imaging center site. The result was small groupings of street segments around each imaging center. Each imaging center could then be evaluated in terms of total population served, average travel time, minimum travel time, maximum travel time, and total accumulated travel time for each partition (the sum of all of the travel times for each group of block group points assigned to each imaging center). These variables could then be compared to those from the location allocation solution sets.

***P*-Median Problem**

As stated previously, the *P*-Median problem is a location allocation model designed to "to minimize the total demand-weighted travel distance between demands and facilities" (Owen & Daskin, 1998). It was first considered by S. L. Hakimi in 1964 when he proposed a way to locate facilities on a network such that the distance between the customers (demand nodes) and their closest facility (supply nodes) would be minimized over the entire network (Hakimi, 1964). The *P*-median problem can be formulated as an optimization model called an *integer programming problem* (IP) (Kemp, 2007). The following notation allows the *P*-median problem to be formulated mathematically:

Minimize $\sum_{i \in I} \sum_{j \in J} h_i d_{ij} Y_{ij}$ (1)

Subject to: $\sum_{j \in J} Y_{ij} = 1 \quad \forall i \in I$ (2)

$\sum_{j \in J} X_j = P$ (3)

$Y_{ij} - X_j \leq 0 \quad \forall i \in I; j \in J$ (4)

$X_j \in \{0, 1\} \quad \forall j \in J$ (5)

$Y_{ij} \in \{0, 1\} \quad \forall i \in I; j \in J$ (6)

Inputs:

i = index of demand node

j = index of potential facility site

h_i = demand at node $i \in I$

d_{iu} = distance between demand node i and potential facility site j

P = number of facilities to be located

Decision variables:

$$X_j = \begin{cases} 1 \text{ if we locate at potential facility site } j \in J \\ 0 \text{ if not} \end{cases}$$

$$Y_{ij} = \begin{cases} 1 \text{ if demands at node } i \in I \text{ are served by a facility at node } j \in J \\ 0 \text{ if not} \end{cases}$$

The objective (1) function minimizes the total demand-weighted distance between each demand node and the nearest facility (or between customers and facilities). Constraint (2) requires that each demand node $i \in I$ be assigned to exactly one facility $j \in J$. Constraint (3) states that exactly P facilities are to be located. Constraint (4) links the location variables (X_j) and the allocation variables (Y_{ij}) and states that demands at node $i \in I$ can only be assigned to a facility at location $j \in J$ (Y_{ij} = 1) if a facility is located at node $j \in J$ (X_j = 1). Constraints (5) and (6) are standard integrality conditions. In an uncapacitated problem such as this, the demands will be assigned entirely to the nearest facility. As a result, constraint (6) may be relaxed to a simple non-negativity constraint such that $Y_{ij} \geq 0$ (Daskin, 2013; Owen & Daskin, 1998).

The P-median problem becomes difficult to solve optimally with increasing values of N nodes and P sites. By limiting the number of potential facility sites to nodes on a network, the number of possible location configurations may be described by $\binom{N}{P} = \frac{N!}{P!(N-P)!}$. For a fixed value of P, the P-median problem can be solved in polynomial time. However, even with a reasonable number of nodes (e.g., hundreds to thousands) and sites (e.g., tens), the problem would require a prohibitive amount of computational time. For example, if N = 50 and P = 10, then $\binom{50}{10} = 10^{10}$. This problem is considered NP-hard (Garey & Johnson, 1990). NP-hard problems are NP (nondeterministic polynomial time) problems that can be reduced to a different problem. For example, if there is a solution to Problem A and, as a result, a solution to Problem B can be constructed, then Problem B can be reduced to Problem A. NP problems are problems that can be solved in polynomial time on a nondeterministic Turing machine rather than a computer (Su, 2013).

Because of the complexity of finding an optimal solution for the *P*-median problem, sophisticated heuristic algorithms have been developed. In 1968, Teitz and Bart proposed an exchange heuristic for the *P*-median problem (Teitz & Bart, 1968). Their method requires the following steps: (1) select an initial set of *P* sites as a solution to the problem, (2) allocate the *N* demand nodes to the *P* sites by calculating the shortest path between each *N* node and *P* site, (3) for each *P* site which is in the initial solution set, substitute a different *P* site outside of the solution set, (4) recalculate the distances between the *P* sites and *N* nodes, (5) if the distance for the second solution is shorter than that for the first solution, keep the second solution, (6) repeat this process iteratively until all existing sites have been considered for removal and no further improvement can be achieved (Daskin, 2013). This particular heuristic is used by TransCAD 6.0 to solve facility location problems. Other heuristic algorithms developed to solve the *P*-median problem include a myopic algorithm in which a good solution is built from scratch and a neighborhood search algorithm which is an improvement algorithm similar in spirit to the exchange algorithm (Daskin, 2013).

Maximal Covering Problem

As defined in the introduction, the Maximal Covering Problem is a location allocation model designed to minimize the maximum distance between any demand node and its nearest facility (Owen & Daskin, 1998). It is considered here as an alternative to the *P*-Median Problem because although the *P*-Median Problem will minimize the average travel time for an entire network, certain individual points will have a much higher travel time creating inequality. The Maximal Covering Problem is designed to reduce this potential inequality by ensuring that all nodes are within a given distance (or travel time) of the desired destination. The following additional notation allows the Maximal Covering Problem to be formulated mathematically:

Minimize $\sum_j c_j X_j$ (7)

Subject to: $\sum_{j \in N_i} X_j \geq 1 \quad \forall i,$ (8)

$X_j \in \{0, 1\} \; \forall_i$ (9)

Inputs:

c_j = fixed cost of siting a facility at node *j*

S = maximum acceptable service distance (or time)

N_i = set of facility sites *j* within acceptable distance of node *I* (i.e., $N_i = \{j \mid d_{ij} \leq S\}$)

The cost of facility location is minimized in objection function (7) while constraint (8) ensures that all demands *i* have at least one facility located within the desired service distance. Constraint (9) requires integrality for the decision variables (Owen & Daskin, 1998, p. 427).

Clustering and Partitioning

A third approach to locating these imaging centers was considered because of an inability to set a capacity constraint in terms of the total population served by each imaging center using each of the previous methods. Clustering allows an analyst to "create groupings of features in a point or area layer based on the distance or travel cost between them, with or without capacity restriction" (*TransCAD*, 2015, p.64). Regional partitioning is used when there is a need "to create compact and balanced areas that are composed of smaller geographic areas" (*TransCAD*, 2015, p. 64). In this case, the clustering procedure was used to create a selection set called seeds upon which the partitioning procedure was based. The goal of the clustering algorithm is to minimize the total cost of travel between the cluster seeds and the rest of the elements in the cluster within the limits of a particular capacity constraint (Koskosidis & Powell, 1992). With the seeds identified, the partitioning algorithm then operates as a two stage heuristic. Initial partitions are created based on the seed zones with the caveat that all features included in the partition must be contiguous. The heuristic then improves upon this initial result by balancing the size of each partition while maintaining contiguity and compactness. When no additional improvement can be found that will reduce the total weight of the partition or balance size among the partitions, the algorithm ceases (Horn, 1995; Zoltners & Sinha, 1983).

In order to determine a capacity restriction for the clustering algorithm, it was necessary to estimate how many individuals could reasonably be assigned to each imaging center based on the average operating capacity of the imaging equipment. For a CT scanner, many variables factor into the determination of operating capacity including the number of slices or images required for each exam, the availability of medical staff to operate the equipment and interpret the images, and facility operating hours. Because of this complexity, medical imaging equipment usage data from the Organisation for Economic Cooperation and Development was utilized to develop a rough estimate. In 2013, approximately 76,000,000 CT scans were performed in the United States. This is equivalent to about 240 scans per 1,000 individuals and 5,529 CT scans per CT scanner (Organisation for Economic Cooperation and Development, 2015). Using the formula (5,529/240) * 1,000, it was estimated that each CT scanner could reasonably support roughly 23,000 individuals. With a population of 1,912,155, the eleven central Indiana counties would require about 83 CT scanners. Only 69 of the identified imaging centers were found to have CT scanners. In the same way, the number of needed MRI machines needed to effectively service the area was estimated. In 2013, approximately 33,800,000 MRIs were performed in the United States. This averaged out to 107 scans per 1,000 individuals and 3,013 MRIs per MRI machine (Organisation for Economic Cooperation and Development, 2015). Using these figures, it was determined that each MRI machine could reasonably support about 28,000 individuals. Based on this calculation, the eleven central Indiana counties would require about 68 MRI machines. 69 of the identified imaging centers were found to have MRI machines. Unfortunately, similar usage data for X-ray services was unable to be found, so no calculations regarding the need for X-ray facilities could be made.

Results

For the current imaging centers in Central Indiana, 71 centers were allocated to population groups using the shortest path method. Ten centers were not allocated any population groups. The average travel time for each partition ranged from 0.9 minutes to 13.8 minutes. The minimum travel time for each partition ranged from 0.1 minutes to 5.7 minutes. Not surprisingly, the longest travel time (35.9 minutes) was attributed to one population point in a rural portion of the network serviced by the IU Health Morgan Hospital. The total accumulated travel time for each partition (the sum of all of the travel times for each group of block group points assigned to each imaging center) ranged from 1.8 to 455.4 minutes. Figures 1 and 2 and Table 4 provide details for the current network allocation.

The P-Median allocation solution selected three imaging centers: American Health Network Franklin, Indiana University Health Methodist Hospital, and St. Vincent Anderson Regional Hospital (Figure 3 and Table 5). This solution was arrived at within 0.1 seconds. The average travel time from a population site to its assigned imaging center site ranged from 14.2 minutes to 18.8 minutes with a total average travel time of 16 minutes for the entire network. The minimum travel time was 0.4 minutes while the maximum travel time was 60.6 minutes. Because this was an uncapacitated allocation problem, the populations assigned to each imaging center were very likely beyond their service capacities. St. Vincent Anderson Regional Hospital was assigned 219,764 individuals, American Health Network Franklin was assigned 248,424 individuals, and Indiana University Health Methodist Hospital was assigned an impossible 1,441,893 individuals. Three block group centroids were unable to be located on the street network for unknown reasons. As a result, 2,074 individuals were not assigned to an imaging center.

The Maximal Covering allocation problem was unable to arrive at an acceptable solution with only 74 imaging center locations to choose from. The goal of the Maximal Covering allocation problem was to select imaging centers such that no population site would need to travel more than 30 minutes to obtain medical imaging. The drive time to IU Health Morgan Hospital exceeded this limit by 6.1 minutes. All 74 imaging center sites were selected for the solution (Figure 4 and Table 6). The run time for this procedure was 32.9 seconds. The total population served by each site ranged from 1,207 to 92,373. The minimum travel time from each population site to its assigned imaging center site ranged from 0.1 minutes to 6.1 minutes. The average travel time ranged from 0.4 minutes to 14.1 minutes. The maximum travel time ranged from 0.4 minutes to 36.1 minutes. Again, three block group centroids containing a total of 2,074 individuals were not assigned to an imaging center. While each of the three unassigned block group centroids had been successfully associated with a street intersection node, a close inspection of the cost matrix revealed that these three street intersection nodes had no cost calculated between themselves and the imaging center destination nodes. As a result, the TransCAD program was unable to assign these block group centroids to an imaging center. A closer inspection of the street network yielded no clues as to why this had occurred.

Because the Maximal Covering allocation algorithm was adversely affected by an insufficient number of imaging sites from which to select, a new approach was taken. A new cost matrix was developed in which travel time was calculated between all possible combinations of block group centroids. Only 39.6 seconds were required to create the new cost matrix. This gave the algorithm a total 1,197 sites to select from when creating a solution.

With this new cost matrix, the Maximal Covering allocation algorithm was able to find a solution limiting the maximum travel time to 30 minutes using just 10 imaging center sites (Figure 5 and Table 7). The run time for this procedure was approximately 2.0 minutes. The total population served by each site ranged from 503 to 530,962. The average travel time ranged from 0 minutes to 19.2 minutes. The maximum travel time ranged from 0 minutes to 29.6 minutes. The minimum travel time for each imaging center site was always 0 minutes since the problem is using travel times to and from block group centroids. Imaging center names were not identified in Figure 5 and Table 7 since those points were not used for this solution.

A Maximal Covering allocation algorithm with a maximum travel time of 15 minutes was also run to see how this affected the number of patients each imaging center was expected to serve. This solution consisted of 36 imaging center sites (Figure 6 and Table 8). The run time for this procedure was 8.3 minutes. The total population served by each site ranged from 503 to 276,184. The average travel time ranged from 0 minutes to 10.4 minutes. The maximum travel time ranged from 0 minutes to 14.7 minutes. Again, the minimum travel time for each imaging center site was always 0 minutes since the problem is using travel times to and from block group population points.

Parameters for the clustering procedure were set such that cluster seeds for 85 clusters with a maximum capacity of 23,000 individuals would be selected. This was based on the smaller of the two figures arrived at when determining how many individuals a CT scanner or MRI machine could reasonably be expected to serve in a given year. The clustering procedure required only 3 iterations performed in 2.3 seconds to find a solution. The largest cluster population was 22,996 while the smallest was 503. The average cluster population was 22,437. The average travel time for the cluster seed locations ranged from 1.7 to 18.8 minutes. These cluster seeds were then used to create partitioned zones for each imaging center location. The partitioning solution required only 3 iterations and 0.1 seconds to create 91 partitions. The smallest partition had a population of 19,418 while the largest had a population of 24,154 which was very close to the goal of 23,000. The average population of all of the partitions was 21,004. Figures 7, 8, 9, and 10 present detailed illustrations of the partitioning result. While the partitioning procedure did not produce a travel time for each zone or partition, the cluster seed result showed that the average travel time for each of the 85 cluster seed locations ranged from 1.7 to 18.8 minutes. This figure was arrived at by dividing the total travel cost (in minutes) for each seed cluster by the number of block groups included in the seed cluster.

Discussion

The stated purpose of this study was to investigate the following five hypotheses:

1. Geographical areas will be identified which currently require driving more than 30 minutes to reach a medical imaging center.
2. The *P*-Median model solution will be more efficient in terms of overall travel time than the current placement of medical imaging centers in central Indiana.
3. The *P*-Median model solution will require fewer medical imaging centers to efficiently service central Indiana.
4. The Maximal Covering model solution will be more efficient in terms of maximum travel time than the current placement of medical imaging centers in central Indiana.
5. The Maximal Covering model solution will require fewer medical imaging centers to equitably service central Indiana.

Network Partitioning Using the Shortest Path Procedure

The first hypothesis was proven to be true. Using the shortest path method to partition the current street network, it was discovered that only one block group centroid was required to drive more than 30 minutes to reach a medical imaging center.

***P*-Median Problem**

The second hypothesis was found to be false. While the total travel time for the current partitioned network was 6,464 minutes (~107 hours), the total travel time for the *P*-Median model solution was 36,831 minutes (~614 hours). The third hypothesis was proven to be true. The *P*-Median model solution required only 3 medical imaging centers to obtain an average travel time of ~16 minutes for the entire street network. However, the maximum travel time for one particular block group centroid was 60.6 minutes. Also, a very large number of individuals were assigned to each of the 3 imaging centers in the *P*-Median model solution. In 2013, the Organization for Economic Co-operation and Development found that approximately 240 CT scans were performed per 1,000 people in the United States (Organisation for Economic Cooperation and Development, 2015). Indiana University Health Methodist Hospital alone was allocated 1,441,893 individuals. If CT demand rates remain stable, this hospital would be expected to perform 346,343 CT scans each year. Considering that each CT scanner in the United States performed an average of 5,529 scans in 2013, 346,343 is likely well beyond the capacity of one CT scanner (Organisation for Economic Cooperation and Development, 2015). Using the same formula, American Health Network in Franklin, Indiana would be expected to perform 59,671 CT scans annually, and St. Vincent Anderson Regional Hospital would be responsible for an additional 52,787 annual CT scans.

Maximal Covering Model

The fourth and fifth hypotheses were not true for the initial solution to the Maximal Covering problem which involved using travel times from each imaging center location to each population point. The highest average travel time for the current configuration was 13.8 minutes while the highest average travel time for the first Maximal Covering model solution was 14.1 minutes. The maximum travel time for the first Maximal Covering model was 36.1 minutes while the maximum travel time for the current configuration was 36.0 minutes. It is interesting to note how close these figures are though. The partitioning of the current network did reveal some room for improving efficiency in that 69 imaging centers were assigned partitions while 10 were not. The first Maximal Covering solution located all available 74 imaging centers.

When the cost matrix for the Maximal Covering algorithm was reconfigured to calculate the cost in travel time between all possible combinations of block group centroids, the highest average travel time increased to 19.2 minutes. The maximum travel time for any one assigned population node dropped to 29.6 minutes. Only 10 imaging centers were needed to service the population in this solution. However, the problem of potential capacity limits appeared again. One imaging center would be expected to service 530,962 individuals for an estimated 127,537 CT scans annually.

The final Maximal Covering solution also used the new cost matrix, but the maximum travel time was changed from 30 minutes (which was used in the previous solution) to 15 minutes. The highest average travel time for this solution was 10.4 minutes while the highest maximum travel time was 14.7 minutes. 36 imaging centers were selected for this solution with the highest assigned population being 276,184. This particular center would need to be prepared to perform roughly 66,339 CT scans annually. While this is likely an unfeasible solution due to potential capacity limits, the solution does meet the criteria for hypotheses four and five, proving them to be true.

Clustering and Partitioning

Although not included in the original hypotheses for the study, perhaps the best solution to this problem was obtained using the clustering and partitioning methods. The final number of imaging centers required (91) was fairly close to the number of existing centers (83); however, the distribution of the imaging centers was considerably different. Because of TransCAD 6.0’s inability to link the results of the partitioning model with the travel times used to create the 91 partitions, it was not possible to compare the drive times of these partitions with those of the other models.

Limitations

There are several limitations to this study. First, the speeds assigned to each of the street segments were inexact. It would be best if accurate speed data could be obtained from local transportation and planning departments, but if that is unachievable, assignments based on the Census Feature Class Code types could be improved. It is unlikely that cars would be using either walkways or bike paths, and so the assigned speeds for these road types could be changed to 0 mph. Speeds assigned to parking lot roads and alleys could also be lowered from 20 or 25 mph to 10 mph. Next, while turn penalties were incorporated into the street network, it would be better if the network also accounted for the time of day during which a driver may be traveling.

Then, it was assumed that all imaging centers are equally accessible. In fact, accessibility may be limited by the nature of the ownership of the imaging centers. As mentioned previously, some imaging equipment is owned by providers who only service their own established patients. For example, an individual requiring an outpatient abdominal CT scan will not be able to be served by a primary care provider with a CT scanner in his office suite unless that patient is already established. Third-party insurance providers may require patients to use a particular network, thus further limiting choice.

While the network partitioning model used the shortest path procedure as an approximation of patient use, it is unlikely that everyone requiring imaging services would only go to the imaging center closest to their home. This study also assumed that travel time is the most important factor when a patient decides which imaging center to use. In reality, this decision may be influenced by the patient's physician's preferences, their insurance network, previous experience with hospital and health care systems, and the opinions of friends and family. The type of imaging services needed will also be important. The imaging centers in this study provided x-ray, CT, <u>or</u> MRI imaging. These services are not equivalent, and yet the imaging center sites were treated as such. In most instances, a particular type of imaging will be required, and centers which do not provide that service will not be considered by a patient. Cost may become a more relevant factor as insurance companies attempt to manage utilization by directing patients to less expensive providers. No studies evaluating the factors influencing patient choice when selecting a medical imaging center were found during the literature search for this study. Analyses within the field of healthcare economics would greatly inform the design of similar location studies in the future.

The service capacity of these imaging centers was not taken into account in some portions of this analysis. In the worst case scenario, one hospital-based imaging center would be expected to provide service for well over 1,000,000 people which is untenable. Also related to imaging capacity, it was assumed that each imaging center had only one piece of equipment for each type of imaging service provided. As a random survey revealed, this is often not the case. Some centers have multiple CT scanners, MRI machines, and/or X-Ray machines.

The representation of population demand by points centered in a block group further deteriorates the accuracy and relevance of this study, but utilizing individual street address points for the nearly 2 million people in the study area would introduce a prohibitive level of complexity for the heuristics available within TransCAD 6.0. Likewise, the alternate solution in which block group population points are used as a substitute for potential imaging center sites is not ideal. Given the time for detailed evaluation of these block group population points, many of them are likely to be in areas not zoned for services such as medical imaging with relatively poor access to major streets and highways.

Conclusion

This study showed that while the *P*-Median and Maximal Covering Models are both useful in efficiently placing resources using a street network, their results are not always feasible. While the *P*-Median Model was very effective at reducing the average travel time for a given network, the Maximal Covering Model is a better choice when placing health care providers on a given network since it is more effective at maintaining equal access to services when equity is assumed to be a function of travel time. The clustering and partitioning procedures were much better at creating compact zones with a population that one imaging center could reasonably service. Ultimately, a capacitated Maximal Covering model would likely produce the best results. This type of model would increase equity of drive time within a given network and ensure that any given imaging center would not be overwhelmed by the population it was assigned to serve.

It is also important to realize that while location allocation analyses are often useful in providing a foundation for informed decision making, they

> may turn out to be of limited use in practice for a range of reasons including: (1) the utility of the modeling approach is not well understood (e.g., through lack of engagement with decision-making bodies); (2) the results fail to serve pragmatic or political ends; and, (3) the results are difficult to implement in practice (e.g., for economic reasons) (Frank Tanser, Gething, & Atkinson, 2009, p. 549).

Future Research and Improvements

Several considerations should be taken into account in future studies. First, accurate speed limit data for the selected road segments would improve the accuracy of the network model upon which this analysis is based. Additional street network attributes such as one-way streets, construction zones, and time of day analysis would further enhance drive time accuracy. Incorporating capacity constraints along with the location allocation models, such as was done by Griffin, Sherrer, and Swann (2008), may produce an outcome as good as or better than that found using clustering and partitioning alone. Determining measurable factors other than travel time which influence which medical imaging center a patient will choose would be of great value when defining the costs and constraints incorporated into the model. For example, if we know that individuals age 65 and older are statistically more likely to need medical imaging, travel time could be multiplied by the number of individuals age 65 and over within each block group. This would create a higher cost in terms of travel time for those areas with aging populations. Finally, directly linking optimization techniques to improved health outcomes, as in McLafferty and Broe's study of acute Coronary Care Units (1990), would significantly increase the relevance and value of this type of location analysis within the healthcare provider community.

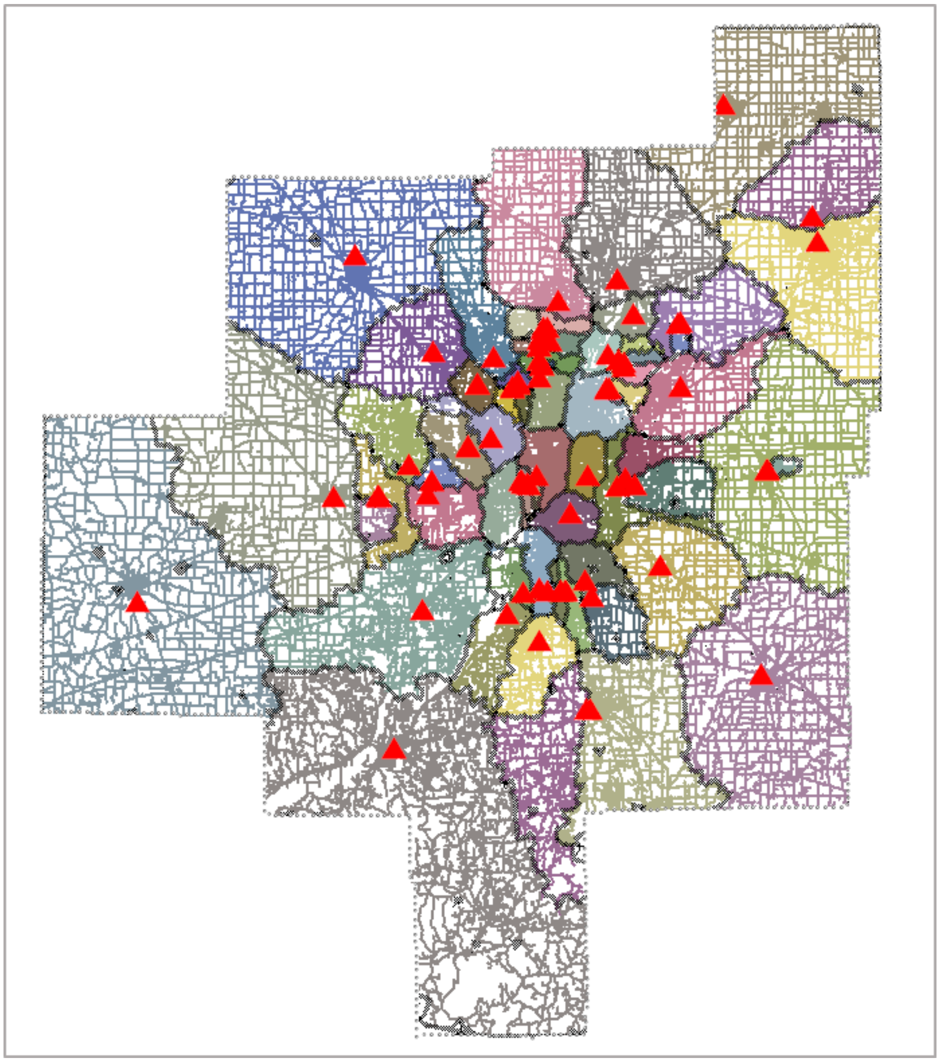

Figure 2. Network Partitioning of Central Indiana Imaging Centers. This figure illustrates shortest path zones created around central Indiana's current imaging center locations.

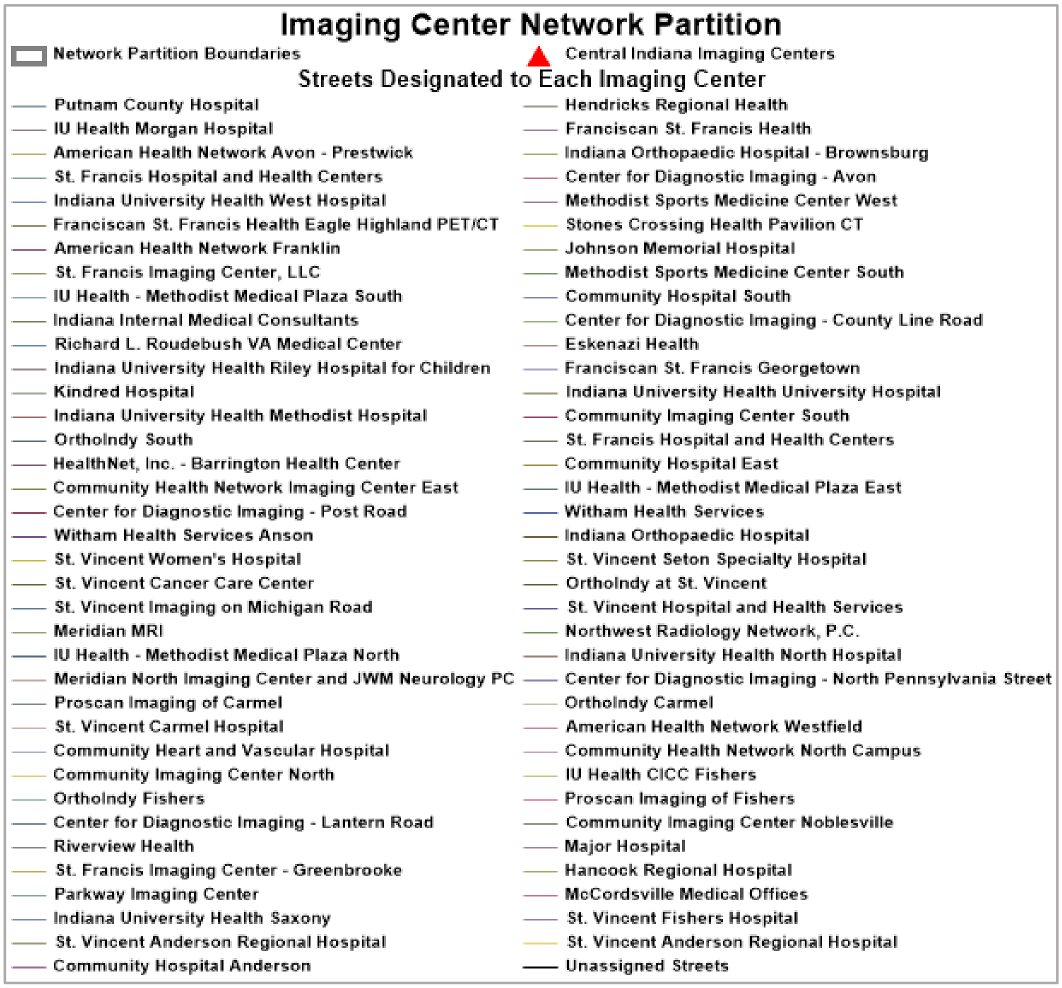

Figure 3. Network Partitioning Legend. This figure illustrates the legend for the map of Network Partitioning of Central Indiana Imaging Centers.

Table 5
Network Partition Allocation for Current Medical Imaging Centers in Central Indiana

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
American Health Network Franklin	13,099	8	13.3	1.9	26.7	106.4
American Health Network Westfield	36,174	14	8.0	0.9	16.9	112.0
Center for Diagnostic Imaging - Avon	44,083	20	5.7	2.2	11.6	112.9
Center for Diagnostic Imaging - Greenwood	30,697	18	3.5	1.0	8.0	63.1
Center for Diagnostic Imaging - Lantern Road, Fishers	7,637	3	4.1	2.0	6.3	12.4
Center for Diagnostic Imaging - N Pennsylvania Avenue, Carmel and Northside ENT	0	0	0.0	0.0	0.0	0.0
Center for Diagnostic Imaging - Post Road	46,958	23	5.0	1.2	7.8	114.0
Community Health Network Imaging Center East	51,935	30	4.1	0.6	11.6	122.1
Community Health Network North Campus	6,348	4	1.4	0.0	4.8	5.6
Community Heart and Vascular Hospital	59,667	38	4.9	0.9	8.1	184.3
Community Hospital Anderson	20,431	19	7.1	1.5	18.5	134.4
Community Hospital East	59,995	65	3.7	0.6	7.3	237.4
Community Hospital South	2,860	2	0.9	0.7	1.1	1.8
Community Imaging Center Noblesville	18,033	7	3.7	1.3	6.8	25.8
Community Imaging Center North	10,728	6	4.4	2.2	7.1	26.2
Community Imaging Center South	0	0	0.0	0.0	0.0	0.0
Eskenazi Health	3,642	3	3.4	1.6	6.0	10.3

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
Franciscan St. Francis Eagle Highland PET/CT and IU Health - Methodist Medical Plaza Eagle Highlands	63,897	35	4.0	0.5	10.7	140.4
Franciscan St. Francis Georgetown	59,084	35	3.3	0.6	5.7	116.6
Franciscan St. Francis Health - Avon	7,942	3	3.0	0.7	4.9	9.1
Hancock Regional Hospital	33,067	24	8.6	0.6	21.4	205.3
HealthNet, Inc. - Barrington Health Center	67,323	62	3.5	0.5	6.3	219.2
Hendricks Regional Health	33,092	24	11.2	1.4	22.8	269.3
Indiana Orthopaedic Hospital - Brownsburg	38,198	14	6.5	3.3	13.0	90.4
Indiana Orthopaedic Hospital and OrthoIndy Northwest	7,991	6	3.1	1.9	4.2	18.6
Indiana University Health Methodist Hospital	**92,319**	**98**	3.9	0.4	7.2	386.1
Indiana University Health Riley Hospital for Children	**2,047**	3	1.5	0.5	2.4	4.6
Indiana University Health Saxony	0	0	0.0	0.0	0.0	0.0
Indiana University Health University Hospital	2,998	3	2.7	0.9	4.3	8.0
Indiana University Health West Hospital	21,722	7	3.0	0.9	4.9	21.3
Indiana University North Health Hospital	6,329	2	3.4	3.2	3.4	6.6
IU Health - Methodist Medical Plaza East	26,673	11	4.5	0.0	9.4	49.4

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
IU Health - Methodist Medical Plaza North	3,387	2	1.2	0.3	2.0	2.3
IU Health - Methodist Medical Plaza South	41,079	22	3.8	1.0	6.8	82.9
IU Health CICC Fishers	8,786	5	2.5	1.4	4.6	12.4
IU Health Morgan Hospital	45,411	33	13.8	0.8	35.9	455.4
Johnson Memorial Hospital	39,311	25	8.1	1.0	24.5	203.0
Kindred Hospital	56,386	49	4.3	0.4	10.2	212.0
Major Hospital	33,276	25	5.6	0.4	16.0	139.0
McCordsville Medical Offices	47,701	19	5.5	2.3	10.2	105.2
Meridian MRI	36,646	31	4.5	0.3	7.5	138.9
Meridian North Imaging Center (JWM Neurology PC)	0	0	0.0	0.0	0.0	0.0
Methodist Sports Medicine Center South	23,221	7	4.2	1.3	10.5	29.4
Methodist Sports Medicine Center West	0	0	0.0	0.0	0.0	0.0
Northwest Radiology Network, P.C. and St. Vincent Heart Center of Indianapolis	11,598	6	3.7	1.8	6.2	21.9
Ortho Indy Carmel and Indiana Spine Group	18,017	10	3.4	0.8	5.6	33.6
OrthoIndy at St. Vincent	0	0	0.0	0.0	0.0	0.0
OrthoIndy Fishers	22,194	11	3.2	0.1	5.9	35.6
OrthoIndy South	11,669	4	6.8	4.1	10.4	27.0
Parkway Imaging Center	5,219	3	1.2	0.8	1.6	3.7
ProScan Imaging of Avon and American Health Network Avon - Prestwick	28,246	16	6.9	3.0	12.9	110.0
ProScan Imaging of Carmel	11,736	1	5.7	5.7	5.7	5.7

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
ProScan Imaging of Fishers	11,364	6	2.9	0.9	4.9	17.3
Putnam County Hospital	33,223	27	10.5	1.3	24.5	284.6
Richard L. Roudebush VA Medical Center	0	0	0.0	0.0	0.0	0.0
Riverview Health	72,435	31	6.3	1.1	13.8	196.5
St. Francis Hospital and Health Centers	52,455	22	4.1	1.7	7.0	90.3
St. Francis Hospital and Health Centers - Mooresville	60,809	32	7.1	1.1	18.5	229.7
St. Francis Imaging Center - Greenbrooke	23,040	13	5.9	2.0	13.2	76.3
St. Francis Imaging Center - Smith Valley Road	13,797	7	3.1	0.8	6.7	21.8
St. Vincent Anderson Regional Hospital	73,395	58	5.3	0.5	16.3	307.7
St. Vincent Cancer Care Center	16,383	10	3.0	0.2	4.9	30.2
St. Vincent Carmel Hospital	20,854	11	3.3	0.6	6.8	36.4
St. Vincent Fishers Hospital	49,285	10	7.8	2.1	12.3	77.9
St. Vincent Hospital and Health Services	13,459	6	2.5	0.8	3.7	14.7
St. Vincent Imaging on Michigan Road	20,968	11	3.4	1.8	7.5	37.1
St. Vincent Mercy Hospital	23,846	33	8.3	0.3	21.7	273.1
St. Vincent Seton Specialty Hospital	0	0	0.0	0.0	0.0	0.0
St. Vincent Women's Hospital	14,952	7	4.1	2.3	5.8	28.9
Stones Crossing Health Pavilion CT	22,394	8	4.6	2.1	8.7	36.8
Urology of Indiana LLC and Indiana Internal Medical Consultants	16,823	12	3.8	0.7	4.6	33.6
Witham Health Services	28,290	26	7.5	1.6	20.5	195.9

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
Witham Health Services Anson	18,740	7	6.2	1.4	10.8	43.4

*The total travel time is the sum of all of the travel times for the block group points assigned to a particular imaging center.

Legend:

Smallest Value in Column	Largest Value in Column

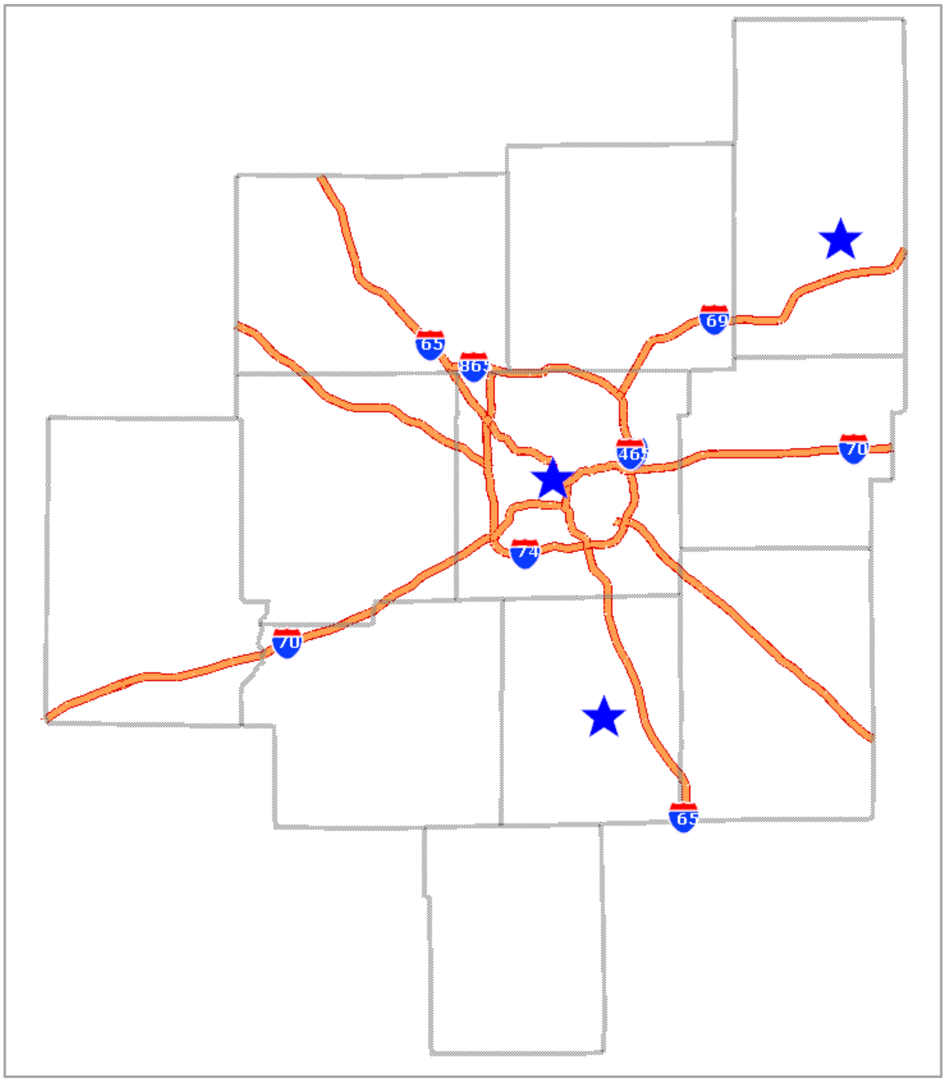

Figure 4. P-Median solution imaging center sites. This figure illustrates the imaging centers selected by the *P*-Median location allocation model.

Table 6
P-Median Solution

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
American Health Network Franklin	248,424	150	**18.8**	**1.2**	46.2	14,350.0
Indiana University Health Methodist Hospital	**1,441,893**	**885**	**14.2**	0.5	60.6	**16,141.5**
St. Vincent Anderson Regional Hospital	219,764	159	15.1	**0.4**	36.2	**6,340.3**
No Imaging Center Assigned	**2,074**	**3**	0	0	0	0

*The total travel time is the sum of all of the travel times for the block group points assigned to a particular imaging center.

Legend:

Smallest Value in Column	**Largest Value in Column**

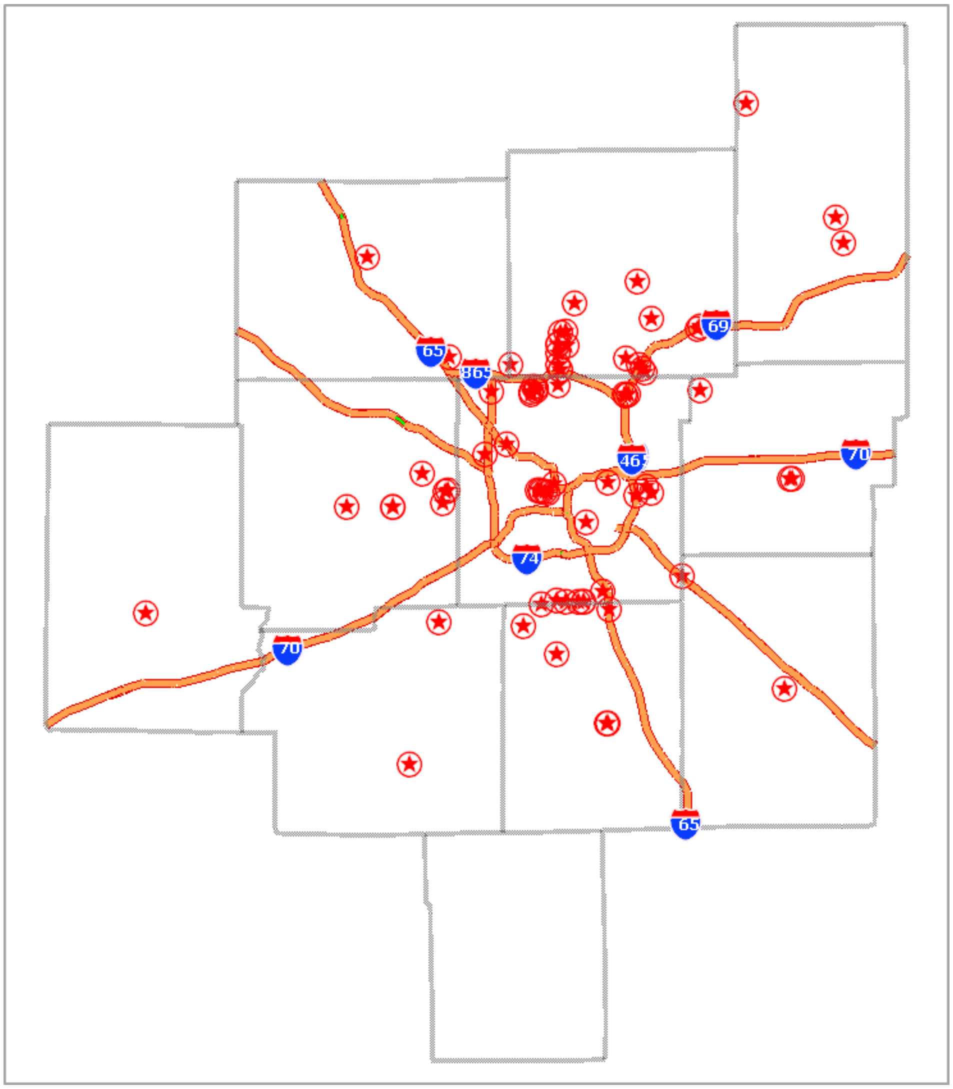

Figure 5. Maximal Covering solution 1 imaging center sites. This figure illustrates the imaging centers selected by the first Maximal Covering location allocation model which used the imaging center sites as possible locations with a maximum travel time of 30 minutes.

Table 7

Maximal Covering Solution 1

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
American Health Network Franklin	13,099	8	13.7	2.4	26.7	1,386.5
American Health Network Westfield	36,174	14	8.4	0.9	18.0	570.7
Center for Diagnostic Imaging - Avon	42,179	19	5.7	2.2	12.0	444.6
Center for Diagnostic Imaging - Greenwood	32,114	19	3.6	1.1	8.2	1,143.1
Center for Diagnostic Imaging - Lantern Road, Fishers	9,718	4	4.6	2.3	6.6	992.9
Center for Diagnostic Imaging - Post Road	45,387	22	5.0	1.2	8.4	1,979.1
Community Health Network Imaging Center East	55,659	33	4.3	0.7	11.6	2,448.0
Community Health Network North Campus	5,754	4	2.2	0.0	4.8	8.9
Community Heart and Vascular Hospital	61,131	39	5.1	1.2	8.9	1,319.9
Community Hospital Anderson	21,621	19	7.2	1.5	16.4	745.4

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
Community Hospital East	60,114	65	3.8	0.6	7.3	707.0
Community Hospital South	1,928	1	1.2	1.2	1.2	1.2
Community Imaging Center Noblesville	15,332	6	3.9	1.4	7.1	120.1
Community Imaging Center North	10,728	6	4.4	2.3	7.1	957.4
Eskenazi Health	3,642	3	3.5	1.7	5.9	42.3
Franciscan St. Francis Eagle Highland PET/CT and IU Health - Methodist Medical Plaza Eagle Highlands	60,110	36	4.0	0.9	6.6	872.3
Franciscan St. Francis Georgetown	59,753	35	3.6	0.6	5.8	2,592.4
Franciscan St. Francis Health - Avon	7,942	3	3.2	0.7	5.0	0.94
Hancock Regional Hospital	37,991	24	8.8	0.6	21.4	917.1
HealthNet, Inc. - Barrington Health Center	67,208	62	3.7	0.7	6.3	1,094.7
Hendricks Regional Health	31,964	23	11.4	1.4	22.8	3,385.7
Indiana Orthopaedic Hospital - Brownsburg	44,627	15	7.1	3.3	13.0	2,749.2

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
Indiana Orthopaedic Hospital and OrthoIndy Northwest	7,991	6	3.6	1.9	4.9	48.7
Indiana University Health Methodist Hospital	**92,373**	**98**	4.0	0.5	7.4	1,988.7
Indiana University Health Riley Hospital for Children	2,074	3	1.6	0.6	2.4	101.6
Indiana University Health University Hospital	2,998	3	3.7	0.9	4.3	50.3
Indiana University Health West Hospital	21,722	7	3.4	0.9	4.9	173.7
Indiana University North Health Hospital	6,329	2	3.3	3.2	3.4	6.6
IU Health - Methodist Medical Plaza East	26,673	11	4.8	1.6	9.8	2,032.9
IU Health - Methodist Medical Plaza North	2,180	1	2.1	2.1	2.1	2.1
IU Health - Methodist Medical Plaza South	42,011	23	3.8	1.0	6.8	445.1
IU Health CICC Fishers	8,786	5	2.7	1.9	4.6	44.8
IU Health Morgan Hospital	45,411	33	**14.1**	0.9	**36.1**	777.2
Johnson Memorial Hospital	39,311	25	8.4	1.0	24.7	**4,714.5**

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
Kindred Hospital	54,893	48	4.5	0.5	10.3	1,047.3
Major Hospital	33,276	25	5.7	0.5	16.0	417.4
McCordsville Medical Offices	46,949	18	5.7	2.3	10.3	1,074.3
Meridian MRI	35,450	30	4.4	0.5	7.6	176.7
Methodist Sports Medicine Center North	**1,207**	**1**	**0.0**	0.0	0.0	0.0
Methodist Sports Medicine Center South	23,211	7	4.5	1.5	10.5	721.5
No Imaging Center Assigned	2,074	3	0.0	0.0	0.0	0.0
Northwest Radiology Network, P.C. and St. Vincent Heart Center of Indianapolis	11,598	6	3.8	1.8	6.2	391.5
Ortho Indy Carmel and Indiana Spine Group	18,017	10	3.6	0.8	5.7	254.0
Ortho Indy Fishers	22,194	11	3.3	**0.1**	5.9	140.2
Ortho Indy South	11,669	4	7.1	4.1	11.5	1,216.1
Parkway Imaging Center	5,219	3	1.4	0.8	2.0	4.2
ProScan Imaging of Avon and American Health Network Avon - Prestwick	28,246	16	7.1	3.0	13.3	214.5

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
ProScan Imaging of Carmel	11,736	1	6.1	6.1	6.1	6.1
ProScan Imaging of Fishers	9,283	5	2.9	1.0	5.0	43.8
Putnam County Hospital	35,489	29	11.5	1.3	24.5	477.0
Riverview Health	74,283	31	6.3	1.2	15.1	1,117.7
St. Francis Hospital and Health Centers	47,642	20	4.4	1.7	7.0	993.7
St. Francis Hospital and Health Centers - Mooresville	59,671	31	7.0	1.2	16.4	1,135.7
St. Francis Imaging Center - Greenbrooke	21,044	12	6.2	2.7	13.5	2,301.0
St. Francis Imaging Center - Smith Valley Road	13,797	7	3.3	0.8	7.2	1,035.0
St. Vincent Anderson Regional Hospital	73,395	58	5.5	0.4	16.5	631.1
St. Vincent Cancer Care Center	14,730	9	3.5	2.2	5.2	116.2
St. Vincent Carmel Hospital	20,854	11	3.4	0.7	6.9	387.5
St. Vincent Fishers Hospital	50,047	11	8.0	2.1	12.6	212.9
St. Vincent Hospital and Health Services	14,578	7	2.6	0.8	3.7	168.4

Imaging Center Name	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
St. Vincent Imaging on Michigan Road	19,849	10	3.6	1.8	7.5	227.7
St. Vincent Mercy Hospital	23,509	34	8.8	0.5	21.7	738.9
St. Vincent Seton Specialty Hospital	1,653	1	0.4	0.4	**0.4**	**0.4**
St. Vincent Women's Hospital	14,952	7	4.2	2.5	6.0	53.3
Stones Crossing Health Pavilion CT	22,394	8	4.5	1.7	8.7	246.9
Urology of Indiana LLC and Indiana Internal Medical Consultants	20,209	13	3.0	0.7	4.9	87.6
Witham Health Services	28,290	26	7.9	1.6	20.7	434.5
Witham Health Services Anson	18,740	7	6.3	1.4	11.2	250.5

*The total travel time is the sum of all of the travel times for the block group points assigned to a particular imaging center.

Legend:

Smallest Value in Column	**Largest Value in Column**

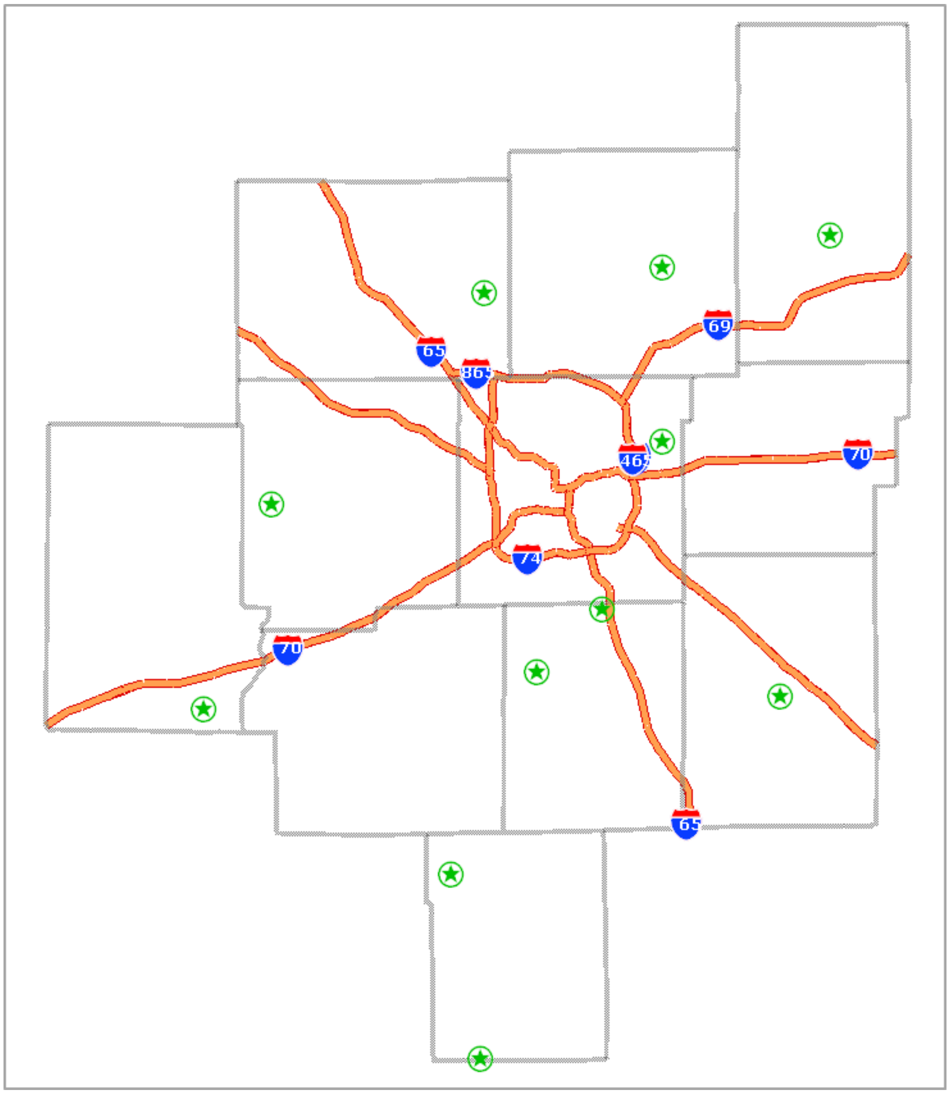

Figure 6. Maximal Covering solution 2 imaging center sites. This figure illustrates the imaging centers selected by the second Maximal Covering location allocation model which used block group population centroids as possible imaging center sites with a maximum travel time of 30 minutes.

Table 8

Maximal Covering Solution Using 30 Minute Travel Limit To and From Block Group Points

Facility ID	Total Population Served	Total Block Groups Served	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
930127585	**503**	1	**0.0**	0.0	**0.0**	**0.0**
930537615	1,571	1	0.0	0.0	0.0	0.0
927943504	18,661	16	**19.2**	0.0	29.2	306.9
927434127	29,829	29	16.5	0.0	28.0	479.4
950179647	108,303	65	15.5	0.0	29.5	1,010.1
961100097	120,670	107	10.6	0.0	29.1	1,131.0
927609005	196,886	101	18.7	0.0	27.5	1,891.2
940887575	409,779	260	17.9	0.0	27.9	4,646.7
941783938	484,991	268	18.7	0.0	**29.6**	5,016.5
929264355	**530,962**	**348**	18.9	0.0	28.9	**6,575.2**

*The total travel time is the sum of all of the travel times for the block group points assigned to a particular imaging center.

Legend:

Smallest Value in Column	**Largest Value in Column**

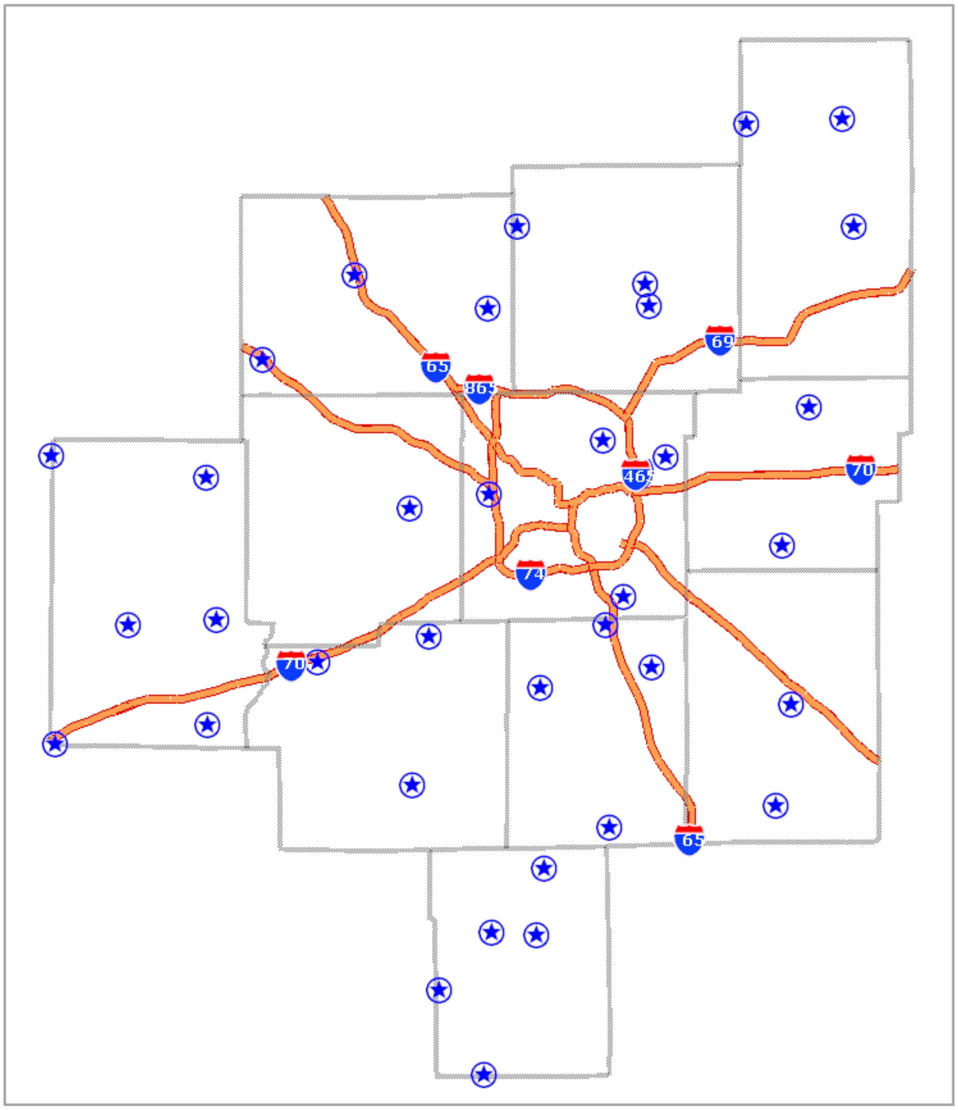

Figure 7. Maximal Covering solution 3 imaging center sites. This figure illustrates the imaging centers selected by the second Maximal Covering location allocation model which used block group population centroids as possible imaging center sites with a maximum travel time of 15 minutes.

Table 9

Maximal Covering Solution Using 15 Minute Travel Limit To and From Block Group Points

Facility ID	Total Population	Total Number of Block Groups	Average Travel Time (Minutes)	Minimum Travel Time (Minutes)	Maximum Travel Time (Minutes)	Total Travel Time* (Minutes)
930127585	**503**	1	**0.0**	0.0	**0.0**	**0.0**
927914091	550	2	3.0	0.0	5.9	5.9
927100512	717	3	5.8	0.0	8.7	17.4
930537615	1,571	1	0.0	0.0	0.0	0.0
927285824	1,736	3	5.8	0.0	11.7	17.5
928167294	3,210	2	5.8	0.0	11.6	11.6
927957940	4,183	4	7.9	0.0	11.6	31.7
950145114	5,192	3	6.9	0.0	10.7	20.6
939582360	6,568	6	7.2	0.0	11.0	43.1
928155783	7,479	5	10.1	0.0	**14.7**	50.4
927545038	7,629	6	8.2	0.0	14.3	48.9
927434127	8,184	4	7.1	0.0	12.8	28.5
941790305	8,947	9	7.3	0.0	14.5	65.7
927576591	9,177	8	10.0	0.0	14.0	79.6
961294384	10,758	16	5.4	0.0	12.8	86.3
929352770	11,802	11	8.8	0.0	12.5	97.1
927537548	12,272	8	9.2	0.0	14.7	73.9
961026961	16,168	21	6.0	0.0	14.3	126.2
941763314	18,594	12	7.6	0.0	13.7	91.2
927295988	18,852	14	6.6	0.0	14.7	19.4
929531638	20,469	10	9.4	0.0	13.8	94.4
940646703	24,485	21	6.6	0.0	12.9	139.2
928371961	28,131	20	6.5	0.0	14.5	129.6
950223085	30,454	24	5.1	0.0	12.2	121.9
950421624	36,274	21	8.9	0.0	14.7	187.7
960915400	40,044	25	10.2	0.0	14.5	255.7
928651648	51,592	26	6.0	0.0	12.6	157.1
961244463	80,693	66	6.9	0.0	14.7	458.1
929264355	95,679	44	9.5	0.0	13.5	419.6
940887575	97,682	36	**10.4**	0.0	14.6	375.1
928732078	101,608	42	7.5	0.0	13.9	316.2
941742433	165,596	52	8.6	0.0	14.2	444.7
930212957	210,740	123	8.9	0.0	14.5	1098.8
941368558	247,121	**192**	7.9	0.0	14.3	**1,518.4**
930476432	251,311	177	7.4	0.0	14.4	1,317.6
929079798	**276,184**	178	7.1	0.0	14.0	1,269.2

*The total travel time is the sum of all of the travel times for the block group points assigned to a particular imaging center.

Legend:

Smallest Value in Column	**Largest Value in Column**

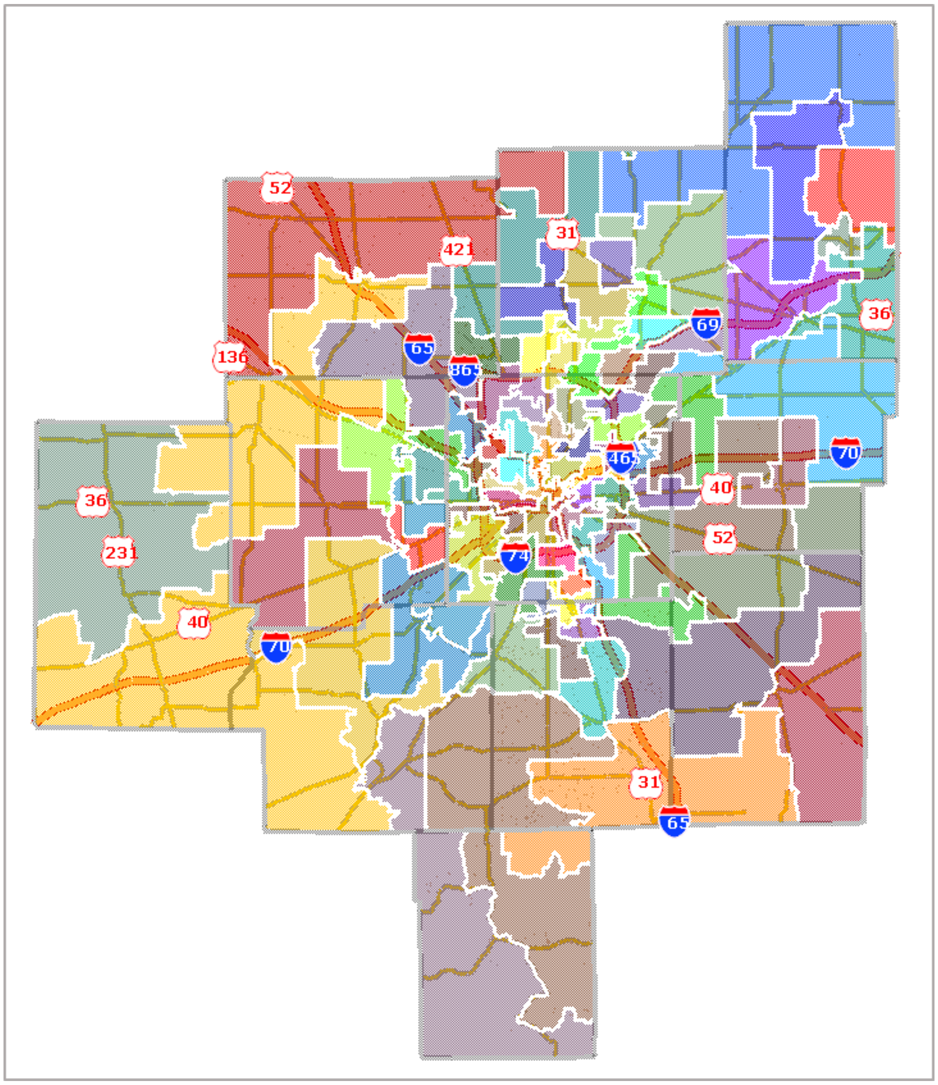

Figure 8. Partitioning solution for 91 imaging center sites. This figure illustrates the 91 partitions or zones with a reasonable number of individuals to be serviced by each imaging center.

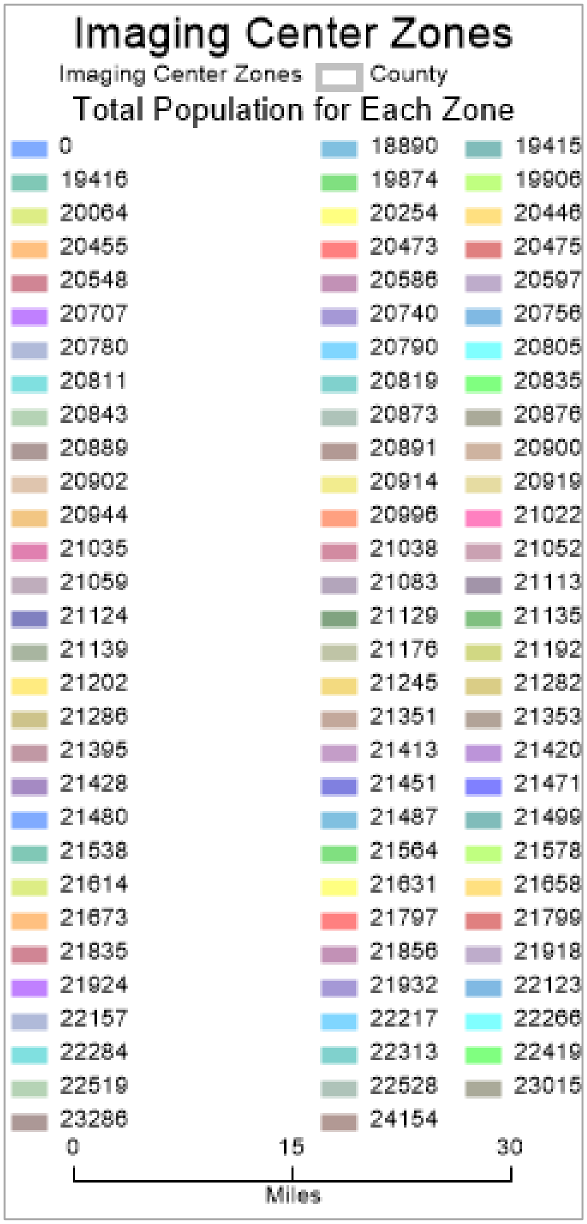

Figure 9. Partitioning solution legend. This figure illustrates the legend for the map of the 91 partitions or zones.

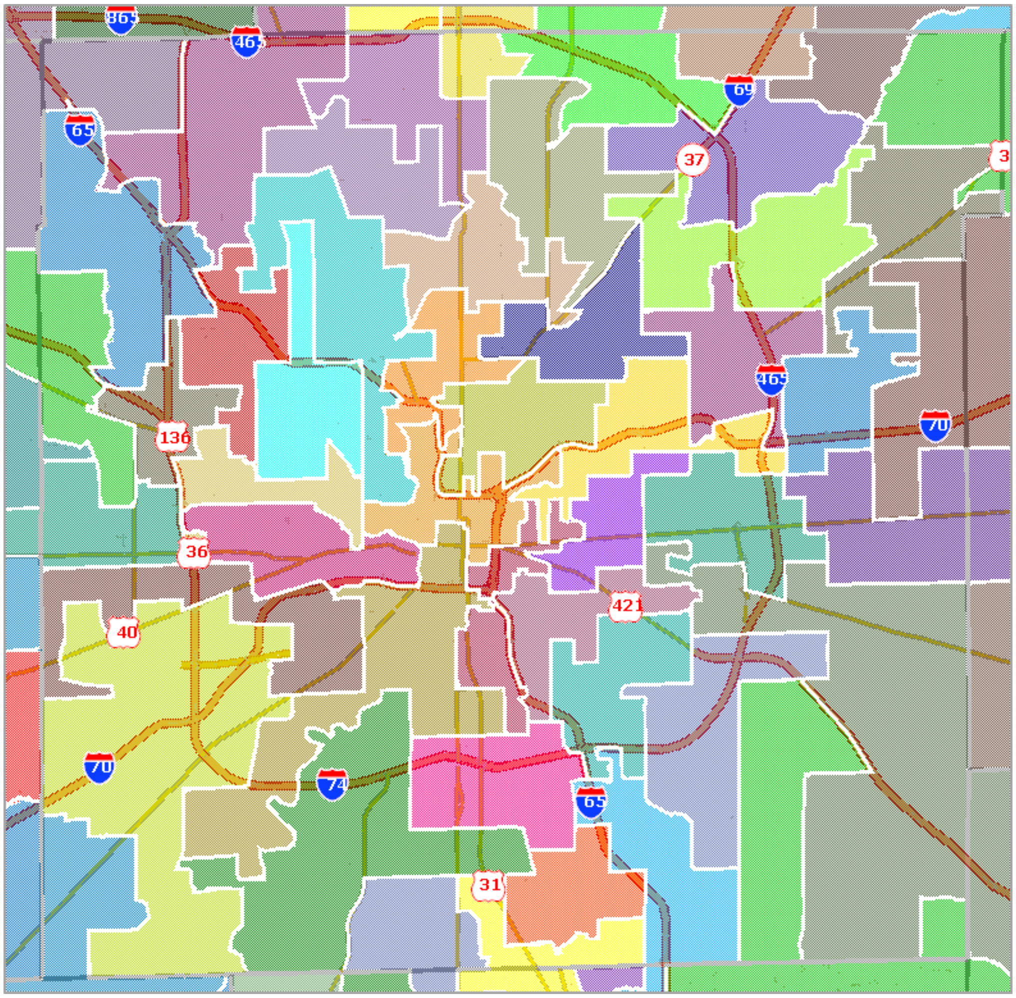

Figure 10. Partitioning solution for Marion County. This figure displays a zoomed-in view of the partitions or zones for Marion County. Each partition represents approximately 23,000 individuals which could be reasonably served by an imaging center.

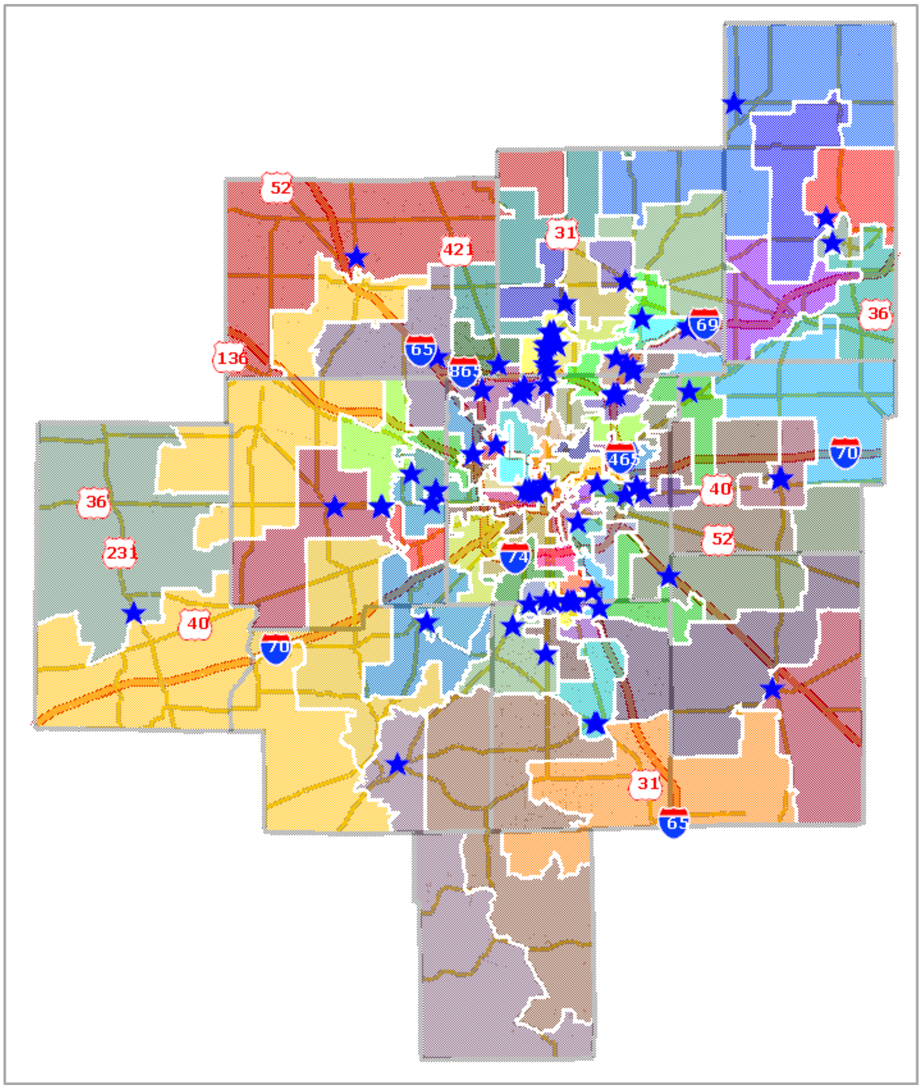

Figure 11. Comparing current imaging center locations with partitioning solution. This figure illustrates how current imaging center locations compare with the solution created by the partitioning procedure.

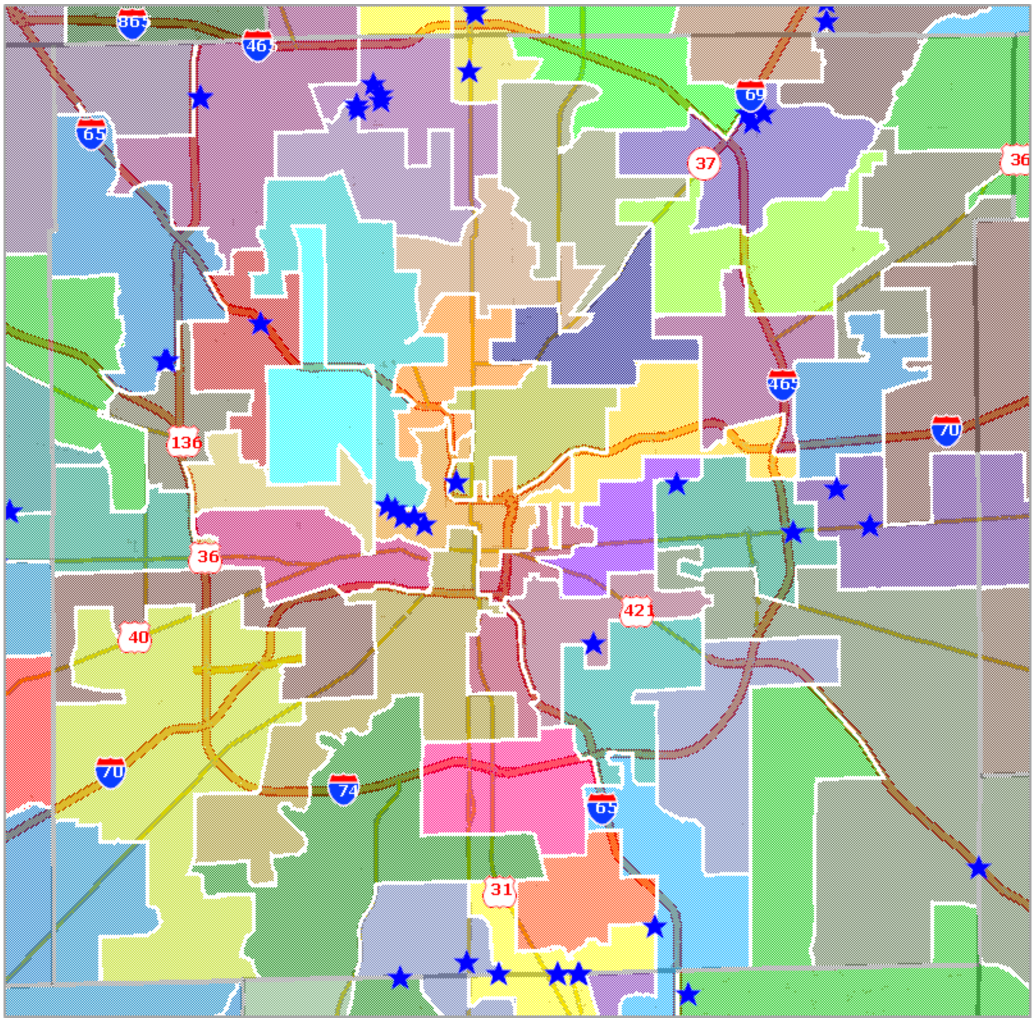

Figure 12. Comparing current imaging center locations in Marion County with partitioning solution. This figure presents a zoomed-in view comparing current imaging center locations in Marion County with the results of the partitioning procedure.

Table 10

Comparing the Current Medical Imaging Network with Location Allocation Model Solutions and Partitioning Solution

Model	Number of Imaging Centers in Solution Set	Largest Population Served by One Center	Total Network Travel Time (Minutes)	Highest Maximum Travel Time (Minutes)	Highest Average Travel Time (Minutes)
Shortest Path Network Partition	71	92,319	6,465	35.9	13.8
P-Median Model	**3**	**1,441,893**	36,832	**60.6**	18.8
Maximal Covering Solution #1	74	92,373	**51,127**	36.1	14.1
Maximal Covering Solution #2	10	530,962	21,057	29.6	**19.2**
Maximal Covering Solution #3	36	276,184	9,218	**14.7**	**10.4**
Partitioning Solution	**91**	**24,154**	**~6,207***	Unknown	~18.8*

*Derived from Cluster Seeds result

Legend:

Smallest Value in Column	**Largest Value in Column**

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The Polis Center, IUPUI, Indianapolis
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Geographic Information Science Intern

- Performed map production upon request
- Created a 30-minute drive catchment using ArcMap 10.1 which was utilized to identify clinics making up the healthcare safety net north of 71st Street in Indianapolis.
- Used Tableau Public, an online data visualization tool, to create maps of data representing Civic Engagement by students at IUPUI and Marian University
- Used WEAVE, a data visualization tool, to create data stories with sociodemographic data for the Domestic Violence Network and the Nurse Family Partnership. The Domestic Violence Network data story is available at http://www.savi.org/savi/Datastories.aspx?vizid=796
- Utilized ArcMap 10.1 to create IMPD Crime Hot Spots intersected with census tracts and block groups to help IMPD target policing efforts
- Used ArcMap 10.1 to create a map of Middle School Math ISTEP Scores by ZIP Code for IPS
- Aggregated sociodemographic variables to Marion County Public Health Department Health Planning Areas using Microsoft Access 2007
- Used ArcMap 10.1 to geocode SAVI asset locations

PROFESSIONAL EXPERIENCE

Academy Allergy, Asthma, and Sinus, Noblesville, Indiana
(January 2008 – Present)
Registered Nurse

- Served as coordinator of insurance authorization and orders for patients requiring replacement IgG infusions due to immune deficiency
- As a clinic nurse, performed all basic clinic duties including giving allergy injections, triaging incoming patient phone calls, performing allergy testing, and providing basic asthma education among other duties

University Medical Center, Pulmonary Outpatient Clinic, Tucson, Arizona
(February 2006 – December 2007)
Registered Nurse

- Served as coordinator of insurance authorization and orders for patients requiring subcutaneous and intravenous infusions for treatment of pulmonary hypertension
- As a clinic nurse, performed all basic clinic duties including rooming patients, performing spirometry testing, triaging incoming patient phone calls, and additional duties as required

Northwest Medical Center, Medical Oncology Unit, Tucson, Arizona
(July 2005 – February 2006)
Registered Nurse

- Provided appropriate nursing care to inpatient medical and oncology clients
- Specific nursing tasks included starting or maintaining intravenous infusions, accessing and maintaining indwelling vascular access ports, dressing changes, care of urinary catheters, monitoring and treating blood sugars, and maintaining heparin drips

Bloomington Hospital, Medical Surgical Unit, Bloomington, Indiana
(May 2003 – June 2005)
Registered Nurse and Charge Nurse

- Functioned as a charge and staff nurse on an 18-bed medical surgical floor in a community hospital serving a small college and rural community
- Provided nursing care for vascular, gastrointestinal, and other medical surgical clients
- Developed expertise in complex wound care, diabetes management, and pre- and post-operative client teaching to a diverse population